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SOME VARIATIONS IN VLF DIURNAL SHIFT

K.J.W. Lynn

SUMMARY

VLF diurnal shifts of differing magnitude have been observed at the same frequency over paired propagation paths of nearly equal length. Computed diurnal shifts demonstrate that a small variation in modal interference spacing with path azimuth may explain these results.

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1. INTRODUCTION

ARAKI(ref.1) has pointed out that ratios of night-to-day signal for the VLF transmitter NWC (North West Cape, Western Australia) received trans-equatorially at Inubo, Japan (on 15.5, 18.0, 19.8 and 22.3 kHz), differ significantly from those reported by LYNN(ref.2) for a middle latitude path of nearly equal length from NWC to Tananarive, Madagascar. He has linked this discrepancy with 18 kHz observations made previously by CHILTON, DIEDE and RADICELLA(ref.3). They found that the diurnal phase and amplitude patterns of NBA (Balbao, Panama) received transequatorially at Tucuman, Brazil, differed significantly from those simultaneously measured at Boulder, Colorado, over a path of approximately the same length.

CHILTON, DIEDE and RADICELLA(ref.3) initially suggested that a latitudinal variation in cosmic ray ionization might provide an explanation of their observations. This view was subsequently modified by changing the latitude-dependent source of ionization to the more recently discovered x-ray stars (CHILTON and CRARY,(ref.4)). ARAKI(ref.1) on the other hand, made detailed calculations based on the assumption that the large variation in VLF propagation parameters observed by LYNN(ref.5), KAISER(ref.6) and MEARA(ref.7) over trans-equatorial paths with an east-west component, would also hold for the trans-equatorial paths NWC - Inubo and NBA - Tucuman, which have a west-east component. Subsequent observations (LYNN,(ref.8)) showed this assumption to be invalid as no substantial variation in VLF propagation parameters was found for trans-equatorial paths where the receiver lay to the magnetic east of the transmitter. However, LYNN(ref.8) presented some evidence to suggest that for night-time conditions, modal interference spacings over west-east paths were slightly less than for middle latitude east-west paths. Further, the proposal was made that this variation could account for the observations of CHILTON, DIEDE and RADICELLA (ref.3) and ARAKI(ref.1). In this paper, this proposal is examined in some detail.

2. THEORY

2.1 The diurnal shift

The total vertical component of electric field at the ground as measured at a distance d from a VLF transmitter can be written as a summation of waveguide modes in the form (WATT,(ref.9)):

$$E = \frac{E_0}{h[a \sin (d/a)]^{\frac{1}{2}}} \sum_m \Lambda_m \exp - (\alpha_m + i \frac{kc}{\upsilon_m})d \qquad (1)$$

Where E_0 = a transmitter constant

h = height of the waveguide

Λ_m = excitation factor of the mth mode

υ_m = phase velocity of the mth mode

α_m = attenuation of the mth mode

k = free space wave number

c = velocity of light in free space

a = radius of the earth

In calculating diurnal shifts, it is convenient to normalise equation (1) by dividing the total field by the field of the first mode to yield

$$\frac{E}{E_1} = 1 + \frac{\Lambda 2}{\Lambda 1} \exp - \left(\Delta\alpha_{21} - i\frac{2\pi}{D_{21}}\right)d$$

$$+ \frac{\Lambda 3}{\Lambda 1} \exp - \left(\Delta\alpha_{31} - i\frac{2\pi}{D_{31}}\right)d$$

$$+ \ldots\ldots\ldots\ldots \qquad (2)$$

$$\text{where } \Delta\alpha_{mn} = \alpha_m - \alpha_n$$

$$\text{and } D_{mn} = \frac{2\pi}{kc}\left(\frac{1}{v_m} - \frac{1}{v_n}\right).$$

The above equations are general. In the following equations, the day and night field parameters are distinguished by superscripts D and N respectively

The change in ionospheric reflection height from day to night produces a diurnal variation in the phase and amplitude of a received VLF signal. The total diurnal phase shift ΔT can be found by subtracting the arguments of the summed day and night field vectors, thus

$$\Delta T = \arg E^D - \arg E^N$$

$$= \arg E_1^D - \arg E_1^N + \arg\left(\frac{E^D}{E_1^D}\right) - \arg\left(\frac{E^N}{E_1^N}\right)$$

$$= \Delta T_1 + \arg\left(\frac{E^D}{E_1^D}\right) - \arg\left(\frac{E^N}{E_1^N}\right). \qquad (3)$$

Here ΔT_1 is the magnitude of the diurnal phase shift which would be observed if only single mode propagation occurred, i.e.

$$\Delta T_1 = \arg E_1^D - \arg E_1^N = \arg\left(\frac{\Lambda_1^D}{\Lambda_1^N}\right) + kc\left(\frac{1}{v_1^N} - \frac{1}{v_1^D}\right)d. \qquad (4)$$

The other two terms in equation (3) represent the perturbing effects of higher order modes present when the path is in darkness or in daylight respectively.

The use of normalised fields allows the diurnal phase shift to be expressed entirely in terms of relative modal parameters, the most significant of which are open to experimental measurement. Moreover, the effect of each modal component is more readily isolated. The relative phase of the normalised components, being controlled by the modal interference spacing D_{mn}, varies slowly with distance. This frequently simplifies the task of computation.

The magnitude of the diurnal amplitude shift expressed as a ratio of the night-to-day field strength can then be written as

$$\left|\frac{E^N}{E^D}\right| = \left|\frac{E^N}{E_1^N}\right| \left|\frac{E_1^D}{E^D}\right| \left|\frac{E_1^N}{E_1^D}\right| \qquad (5)$$

where the first mode amplitude ratio is given by

$$\left|\frac{E_1^N}{E_1^D}\right| = \frac{h^D}{h^N} \left|\frac{\Lambda_1^N}{\Lambda_1^D}\right| \exp\,(\alpha_1^D - \alpha_1^N)d \qquad (6)$$

2.2 Parameter models

The modal interference spacing D_{21}^N plays a dominant role in many VLF observations. It causes both the diurnal shift (KAISER,(ref.10)) and the sunrise-sunset transition patterns (CROMBIE,(ref.11)) to differ from single mode expectations. In this paper, the effect on diurnal shift of a small change in D_{21}^N with direction of propagation is considered.

The models of D_{21}^N as a function of frequency for east-west and west-east propagation with respect to the earth's magnetic field are shown in figure 1. These models are based on experimental observations published previously (LYNN,(ref.8)). Theoretical D values given by the isotropic night model of WAIT and SPIES(ref.12) are included for comparison. All other parameters necessary for the calculation of diurnal shift were taken from the isotropic models of WAIT and SPIES(ref.12) with h = 90 km, β = 0.5/km representing night conditions and with h = 75 km, β = 0.3/km representing day. In these models, h represents an effective reflection height and β the gradient of electron density.

From equation (4), the rate of change of first mode diurnal shift with distance is given by $kc\,(1/v_1^N - 1/v_1^D)$. Values of this parameter calculated from the aforementioned isotropic models are shown in figure 2. Included are experimental values found by BLACKBAND and quoted by WAIT(ref.13). The agreement between the model and experimental observation is good at the lower frequencies, becoming less so around the 17 kHz minimum. The absence of experimental results at higher VLF frequencies reflects the impossibility of direct measurement where the first mode diurnal shift is always significantly perturbed by the presence of higher order modes. The day model used has previously been found by RAWLES and BURGESS(ref.14) to give good agreement with experimentally determined measurements of D_{21}^D.

In calculating diurnal shifts, modes of higher order than the second were neglected since their effect over the paths considered were negligible for the theoretical model taken. The directional effects of the earth's magnetic field on the attenuation, the excitation parameters and first mode diurnal shift were also neglected so that the effect of changing D_{21}^{N} could be more clearly seen. These parameters mainly control the magnitude of the diurnal shift perturbations rather than their location as a function of frequency or distance.

3. NWC DIURNAL SHIFTS

Values of diurnal phase shift ΔT and the corresponding ratios of night-to-day field strength E^N/E^D are shown in the upper part of figure 3 calculated from the model for the path NWC - Inubo (6947 km). The diurnal shifts expected for single mode propagation are included for reference and the experimental values discussed by ARAKI(ref.1) are indicated. The diurnal phase variation is dominated by the discontinuity occurring in the vicinity of 20 kHz where the two night modal components pass through antiphase with the second mode predominating. Experimentally, diurnal shifts of both 44 μs and 89 μs (one phase cycle greater) are observed at 22.3 kHz. At some times of year, phase cycle losses are observed produced by mode conversion during the sunrise and sunset transitions. The detailed diurnal shift over a sunrise or sunset transition can only be calculated in these circumstances by following the relative phase and amplitudes of the direct and mode converted field components as a function of time (as has been done by SUZUKI et al,(ref.15)). In all cases, the final 22.3 kHz value of diurnal phase shift can differ from that shown only by an integral number of cycles.

Examining the calculated ratio of night-to-day field strength, the model predicts the very low value occurring at 19.8 kHz and the abrupt increase to a higher value at 22.3 kHz.

The corresponding model calculations for the path NWC - Tananarive (6916 km) is shown in the lower part of figure 3 along with phase data supplied by Dr. F. Reder (private communication). The high model values of D_{21}^{N} postulated for this path have lowered the position of the major signal minimum by some 2 kHz. The absence of a phase cycle discontinuity indicates that the amplitude of the first mode exceeded that of the second at this lower frequency.

A comparison of the Inubo and Tananarive data shows that the major differences in the diurnal phase and amplitude values at 18.0 and 19.8 kHz for the two sites is satisfactorily reproduced by the model.

4. NBA DIURNAL SHIFTS

In figure 4, a comparison is made between the calculated and observed values of diurnal phase and amplitude shift over the paths NBA - Tucuman (4292 km) and NBA - Boulder (4275 km). The abnormally low values of night field strength and diurnal phase shift at Tucuman are explained by the proximity of an antiphase point in the night field pattern. The reversal in diurnal phase shift at the end of sunset and beginning of sunrise transitions observed at Tucuman and commented on by CHILTON, DIEDE and RADICELLA(ref.3) is not unusual in these circumstances. The same phase pattern has been observed for NWC (15.5 kHz) transmissions received in Sydney (unpublished data). This effect results from the night-time depression of the diurnal shift from the first mode value as

the second mode gathers strength. The erratic phase and amplitude variations observed at night at Tucuman (and also on the NWC - Tananarive path at 18.0 kHz) are to be expected at a location where dominant modes nearly cancel.

The postulated increase in D_{21}^{N} spacings over the path to Boulder has shifted the antiphase position away from the receiver thus accounting for the observed features, namely stable reception, increased diurnal phase shift and higher night signal levels.

5. DISCUSSION

The calculated and observed diurnal shifts shown in figures 3 and 4 indicate the importance of modal interference in determining the magnitude of diurnal phase and amplitude changes at the higher VLF frequencies. At critical distances where two modes of comparable magnitude are approximately in anti-phase, the diurnal phase shift can differ greatly from the single mode value, being lower when the receiver lies closer to the transmitter than the critical distance and higher when the receiver lies beyond it. Whilst the instability of the signal at such locations may make observations difficult, there exists the possibility that the propagation effects of gross geophysical changes will be magnified at these locations. Thus a small displacement of the modal interference pattern relative to a favourably placed receiver, resulting say from a slow change in reflection height at night or with time of year, may result in unusually large changes in the observed phase and/or amplitude of the signal. The sign of these changes will depend on the precise receiver location. The danger in interpreting such variations in terms of changing reflection height on the basis of a single mode propagation model is evident.

The detailed calculations of diurnal phase and amplitude patterns for the paired paths discussed in this paper support the contention made previously (LYNN,(ref.8)) that the observations of CHILTON, DIEDE and RADICELLA(ref.3) and ARAKI(ref.1) could be accounted for by a slight variation in night-time modal interference spacing as a function of path azimuth. This variation is attributed to the effect of the earth's magnetic field on the ionospheric reflection process. At middle latitudes, the magnitude of this variation is close to the experimental accuracy with which modal interference spacings have been measured from sunrise fading observations. On the other hand, the calculations presented here indicate that the resulting displacement of the diurnal phase and amplitude pattern as a function of frequency may often be observable over VLF paths of moderate length. For this reason, it is to be regretted that multifrequency VLF transmissions are so rare. A practical technique for making frequency scan measurements at VLF is described by HILDEBRAND and ADRIAN(ref.16). Such measurements made simultaneously to the east and to the west of a transmitter could be of great value in determining directional asymmetries in VLF propagation parameters.

6. CONCLUSIONS

Minor changes in relative modal phase velocities can produce significant variations in the magnitude of diurnal phase and amplitude shifts over geographically separated propagation paths of equal length. The experimental observations discussed by ARAKI(ref.1) and CHILTON, DIEDE and RADICELLA(ref.3) can be reproduced satisfactorily by a model in which modal interference spacings at night are some 10% greater for east-west middle latitude paths than for west-east transequatorial ones. This asymmetry is attributed to the directional effect of the earth's magnetic field on VLF propagation parameters.

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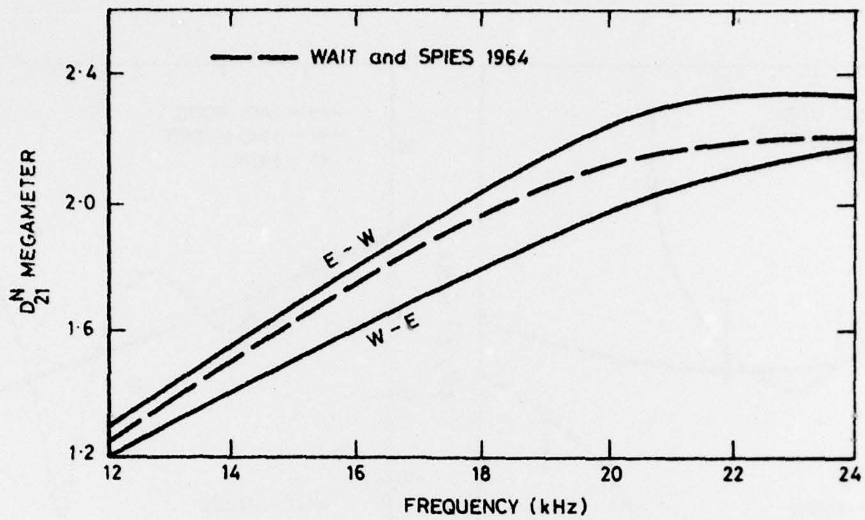

Figure 1. The postulated frequency variation of the night modal interference spacing D_{21}^{N} for E-W and W-E propagation.

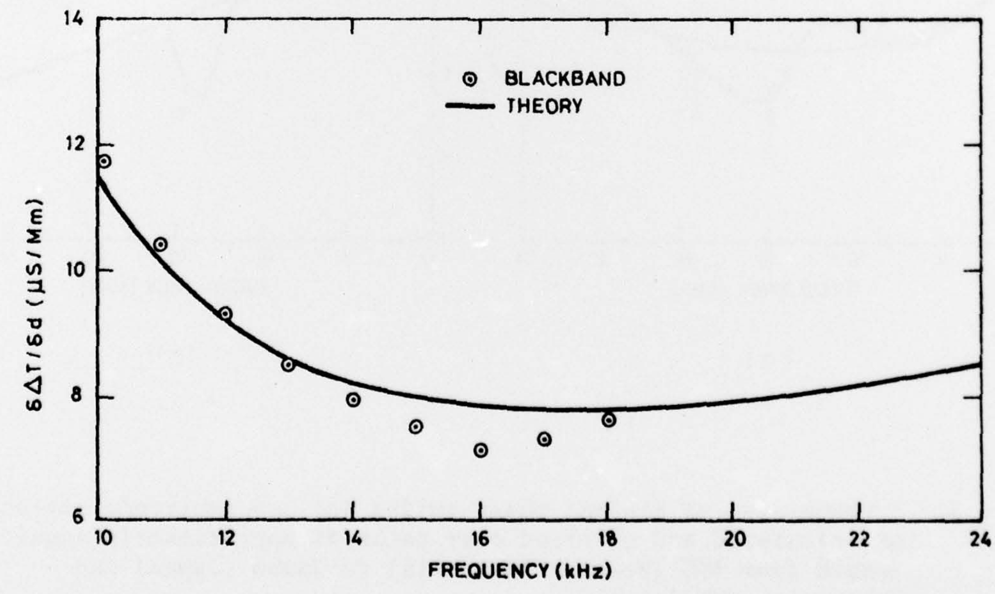

Figure 2. The calculated and observed rate-of-change of single mode diurnal phase shift with distance plotted as a function of frequency

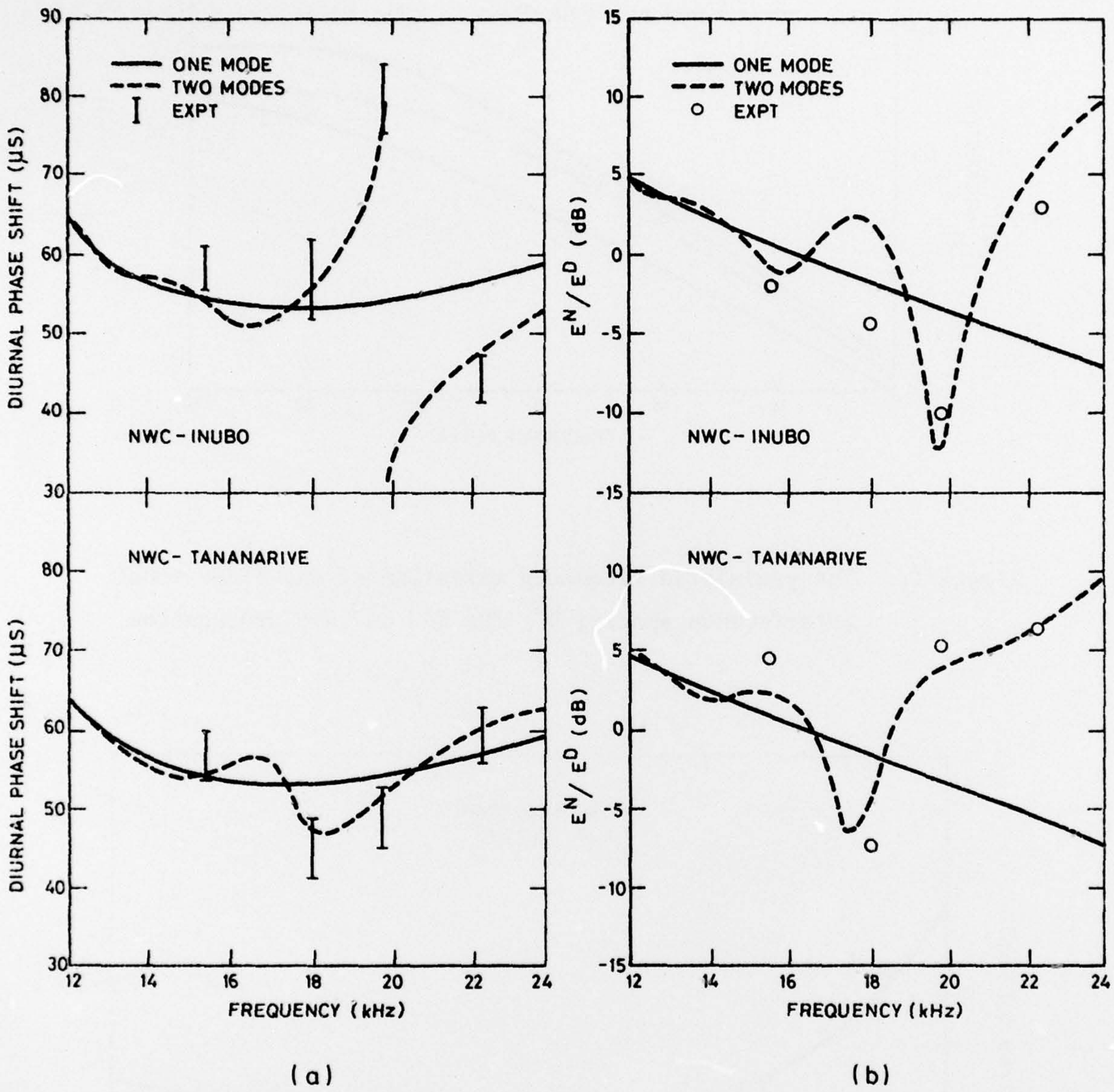

Figure 3. A comparison of diurnal phase shifts (a) and amplitude ratios (b) as calculated and observed over paths of approximately equal length from NWC (Western Australia) to Inubo (Japan) and Tananarive (Madagascar)

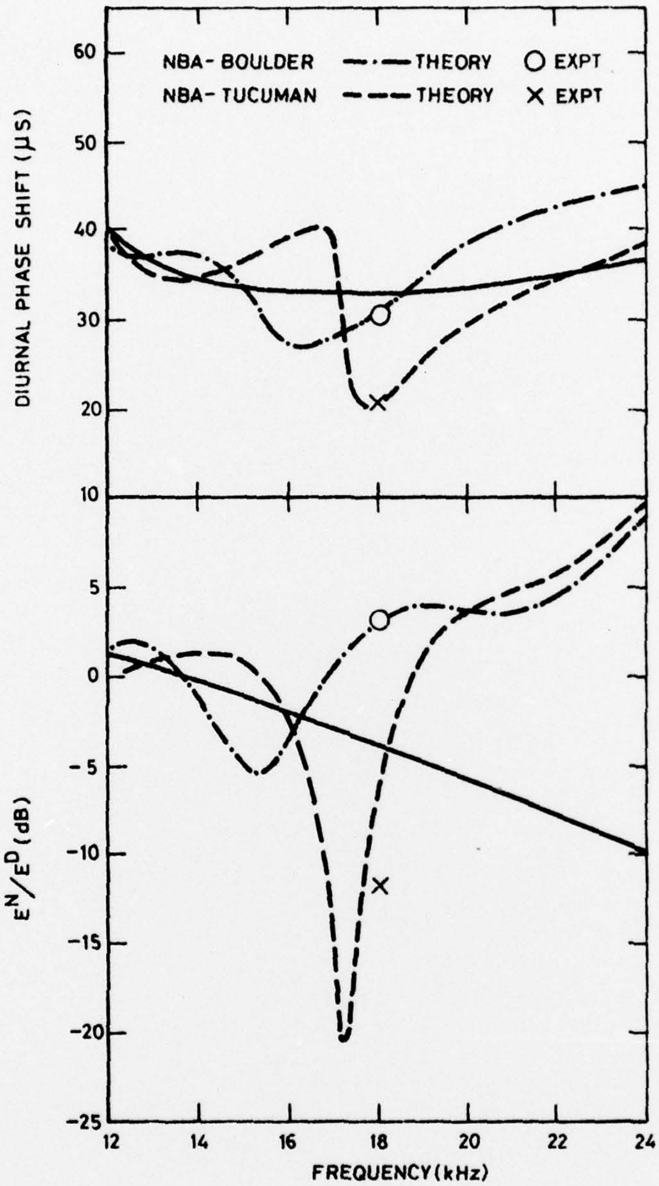

Figure 4. A comparison of diurnal phase shifts and amplitude ratios as calculated and observed over paths of approximately equal length from NBA (Panama) to Tucuman (Brazil) and Boulder (Colorado)

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